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Electronic Warfare Division

RESEARCH NOTE
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A PRELIMINARY DESIGN OF THE Ti:$LiNbO_3$ OPTICAL CHANNEL WAVEGUIDE (U)

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ABSTRACT

One of the goals of technology-based activities within the Electronic Warfare Division is to facilitate the development within Australia, of facilities and a capability to manufacture sophisticated, high-speed electro-optic devices, in particular, the integrated optical amplitude modulator and integrated optical switch, for use in microwave and millimetre-wave systems for the Australian Defence Force (ADF). An initial step towards this goal would be to produce a low-loss and single-mode propagation optical channel waveguide using titanium-indiffused lithium niobate (Ti:$LiNbO_3$). As no dimensions and fabrication parameters have yet been optimised, this technical report provides preliminary design data which optimises these parameters. Depending on its application, the optimised dimensions and fabrication parameters are as follows:

metal strip width, W = 5 to 6 λ_o;
diffusion depth, D = W/4 to W/2; and
metal thickness, τ = 0.025*D to 0.03*D (by electron-beam deposition).

For the Y-branch interferometer at 1.3 µm operating wavelength, the following dimensions and fabrication parameters are chosen:

metal strip width, W = 7 µm;
diffusion depth, D = 3.5 µm; and
metal thickness, τ = 0.1 µm.

Assume that for the commonly used congruent $LiNbO_3$ composition (48.6 mol % Li_2O), the value for the diffusion constant D_o and the characteristic activation temperature T_A is given as 2.5×10^{-4} cm^2/s and 2.55×10^4 °K respectively. Taking the diffusion temperature T as 1025 °C, the diffusion time is calculated as 11.6 hours.

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1 INTRODUCTION

Microwave fibre-optic communication links have several advantages when compared to conventional coaxial and waveguide links. The advantages are greatly reduced size and weight; as the number of transmission paths increases, the weight saving obtained with optical fibre cable increases dramatically; low and constant attenuation over the entire modulation frequency range; impervious to electromagnetic interference (EMI), radio frequency interference (RFI), and electromagnetic pulse (EMP); wide bandwidth; and high information transfer capacity. Applications of fibre-optic links include radar, communication, signal processing and remote sensing.

In general, microwave fibre-optic communication links are of two types. They are the direct modulation link and external modulation link. Direct modulation offers simplicity, low drive power and less overall link loss. On the other hand, the use of external modulators has the following advantages:

1. Chirp due to changes in the current density is avoided, hence the spectral quality of the transmitted optical signal is higher;

2. High modulation extinction without sacrificing the purity of the transmitted signal;

3. Optimized spectral quality and power output without trade-offs to attain high modulation bandwidth;

4. Potentially possible to achieve microwave gain through the optical link (from modulator input to detector output) by increasing the optical power of the laser. Note that microwave output power is proportional to the square of the optical intensity, but modulation depth is proportional to microwave current swing.

The disadvantages of the externally modulated link are non-zero insertion loss and complexity of an additional component in the system. Both of these techniques need to be evaluated for their applicability to a specified system requirement.

One of the goals of technology-based activities within the Electronic Warfare Division is to facilitate the development within Australia, of facilities and a capability to manufacture sophisticated, high-speed electro-optic devices, in particular, the integrated optical amplitude modulator and integrated optical switch, for use in microwave and millimetre-wave systems for the Australian Defence Force (ADF). An initial step towards this goal would be to produce a low-loss and single-mode propagation, optical channel waveguide using titanium-indiffused lithium niobate (Ti:$LiNbO_3$). As no dimensions and fabrication parameters have yet been optimised, this technical report provides preliminary design data which optimises these parameters.

2 DESIGN OF THE Ti:$LiNbO_3$ OPTICAL CHANNEL WAVEGUIDE

Graded-index waveguides currently play a prominent role in integrated optics. Much of the present interest can be attributed to the widespread use of titanium-indiffused lithium niobate (Ti:$LiNbO_3$) waveguides for various types of switching and modulation applications [1]. These waveguides are formed by diffusing titanium into a polished $LiNbO_3$ crystal. The diffusion process creates a higher-index region in the crystal in which the refractive index is largest at the surface and diminishes with increasing depth into the crystal until it reaches the normal value for $LiNbO_3$. Specific details about the theoretical analysis and fabrication process including the various techniques for replacing oxygen that has been lost from the crystal during the diffusion process, or for reduction of Li_2O out-diffusion, which causes unwanted planar waveguiding will be discussed in the subsequent reports.

2.1 Diffusion of Ti into $LiNbO_3$

In the case of diffusion for the purpose of waveguide formation, the diffusion time is long compared to that required to deplete the source compound. Channel waveguides are fabricated by photolithographically defining a stripe of width W from the deposited Ti (Figure 1). The fact that there is no inherent anisotropy observed for diffusion along the different axes of the $LiNbO_3$ crystal [2] greatly simplifies the theoretical analysis of the diffusion from this strip. Under isotropic conditions, the strip may be considered as a continuous set of infinitesimally wide line sources and we may integrate their contributions to obtain the concentration at a specified point. In this case, the theoretical concentration profile is separable in the lateral and vertical coordinates, x and y, and can be written [2] as

$$C(x,y) = C_o * f(x) * g(y) \tag{1}$$

with

$$C_o = \frac{2}{\sqrt{\pi}} * \frac{\tau}{D} * \mathrm{erf}\left(\frac{W}{2D}\right) \tag{1a}$$

$$f(x) = \frac{1}{2 * \mathrm{erf}\left(\frac{W}{2D}\right)} * \left\{\mathrm{erf}\left[\frac{1}{D} * \left(x + \frac{W}{2}\right)\right] - \mathrm{erf}\left[\frac{1}{D} * \left(x - \frac{W}{2}\right)\right]\right\} \tag{1b}$$

$$g(y) = \exp\left(-\frac{y}{D}\right)^2 \tag{1c}$$

where τ is the thickness of the deposited titanium layer before oxidation,
$D = \{4*D_o*[\exp(-T_A/T)]*t\}^{1/2}$, is the diffusion depth, (1d)
D_o is the diffusion constant,
$D_o*\exp(-T_A/T)$ is the diffusivity, (1e)
T_A is the characteristic activation temperature
T is the diffusion temperature,
t is the diffusion time,
W is the value of the initial metal strip width
erf is the error function

Some of the measured values for the diffusivity of the commonly used congruent $LiNbO_3$ composition (48.6 mol % Li_2O) and their corresponding values for D_o and T_A that describe the diffusivity in this temperature region [3] are given in Table 1.

Table 1 Measured values for the diffusivity of the commonly used congruent $LiNbO_3$ composition (48.6 mol % Li_2O) and their corresponding values for D_o and T_A.

Diffusivity (cm^2/s)	T (°C)	D_o (cm^2/s)	T_A (°K)
0.5×10^{-12}	1000		
1.0×10^{-12}	1050	2.5×10^{-4}	2.55×10^4
2.0×10^{-12}	1100		

The diffusion rates depend on the stoichiometry of the $LiNbO_3$ crystal and the diffusion environment. Therefore, the values of D_o and T_A may differ from laboratory to laboratory and must be adjusted accordingly. It is also worth pointing out that the density of deposited titanium is also dependent on the method of deposition. Electron-beam deposition of the titanium yields

a density very close to that of bulk metallic titanium, whereas deposition via resistive thermal evaporation tends to yield a density lower by approximately 25%, and therefore the measured thickness, τ, must be devalued appropriately.

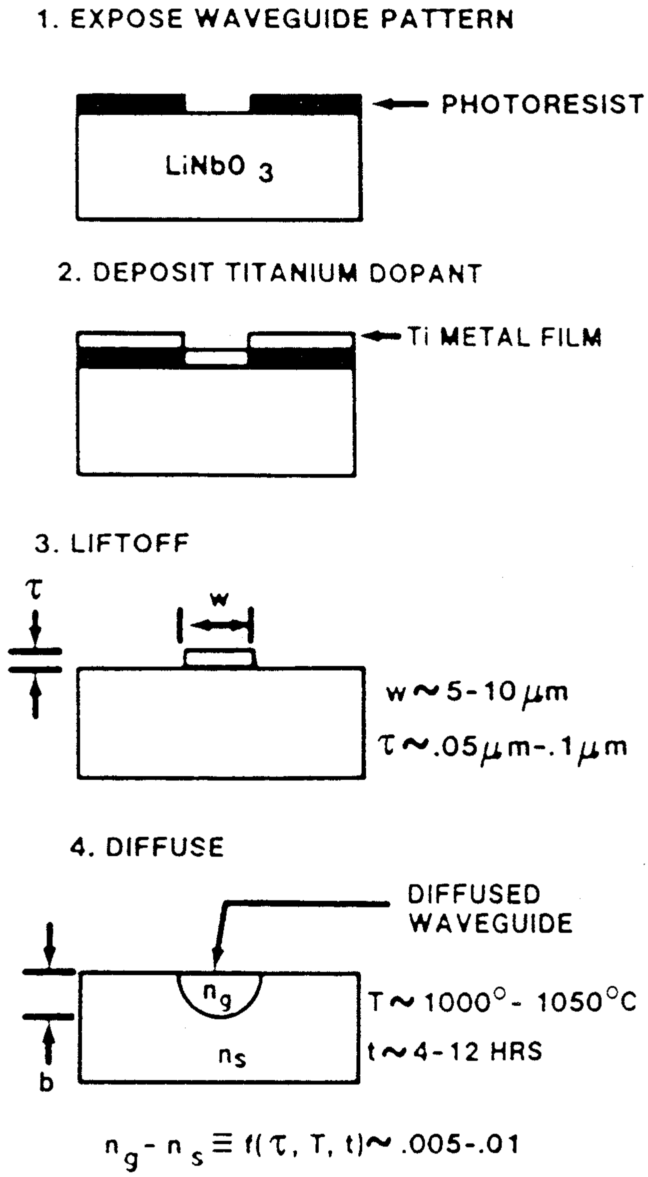

Figure 1 Waveguide fabrication procedure.

2.2 Dependence of Index on Ti Concentration

The index change for the extraordinary axis is directly proportional to the titanium concentration, and the index change for the ordinary axis is a sublinear function of concentration. Figure 2 (Derived from data of reference [4]) showed that the index change for the extraordinary axis is 9.461×10^{-3} for a Ti concentration of 1.5% of the bulk metallic Ti density. Since the index change is proportional to concentration and to a good approximation, we can write

$$\Delta n(x,y) = \Delta n_o * f(x) * g(y) \qquad (2)$$

Having enforced the conservation of the number of Ti atoms, the peak index change Δn_o is given by

$$\Delta n_o = b(\lambda) * C_o = \frac{2}{\sqrt{\pi}} * \frac{b(\lambda) * \tau}{D} * \operatorname{erf}\left(\frac{W}{2D}\right) \qquad (2a)$$

The constant of proportionality, $b(\lambda)$, between index change and percent Ti concentration is approximately 0.63 at $\lambda = 0.5893\ \mu m$. The index change exhibits a small wavelength dependence [5] that can be approximated by

$$b(\lambda) = 0.442 + 0.065/\lambda^2 \quad (\mu m) \qquad (2b)$$

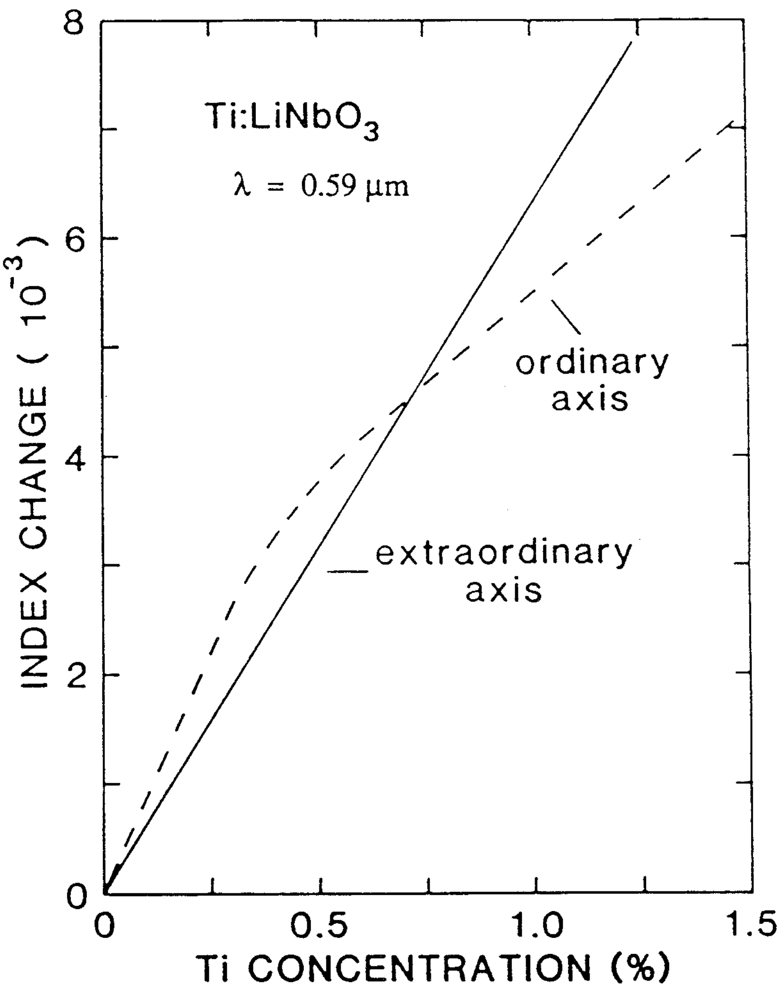

Figure 2 Index change versus titanium concentration.

2.3 Design of the Ti:$LiNbO_3$ Optical Channel Waveguide

The mode sizes for diffusion parameters typical of 1.3 μm wavelength can be calculated using equations (1) and (2) in this report and the field expressions of reference [6]. As the waveguide parameters - waveguide width, effective depth and peak index change - can be independently controlled through the fabrication parameters and none of the parameters has yet been standardised, our initial choice of the diffusion parameters were T = 1025°C, t = 6 hours and τ = 0.09 μm at 1.3 μm wavelength. Figure 3 shows the calculated Ti:$LiNbO_3$ mean mode size at full width half intensity for the above chosen diffusion parameters. It can be seen that the mode size is very large when the strip width is small and guiding is weak. Increasing the strip width reduces the size of the mode as the increasing cross section of the doped region pulls the mode within the waveguide. Once within the waveguide, the mode size reaches a minimum and with further increase of the strip width the mode size begins to increase to follow the waveguide size. For strip widths larger than that required to achieve the minimum size, the guide moves close to the multimode regime. The optimal strip width dimension is characterized by a relative insensitivity of the mode size to variations of the strip width. Hence, for single-mode operation at a wavelength of 1.3 μm, the strip width is chosen to be from 6.5 to 8 μm. That is, for single-mode Ti:$LiNbO_3$ waveguides, the initial metal strip width is empirically $5*\lambda_o$ to $6*\lambda_o$, where λ_o is the free-space operating wavelength.

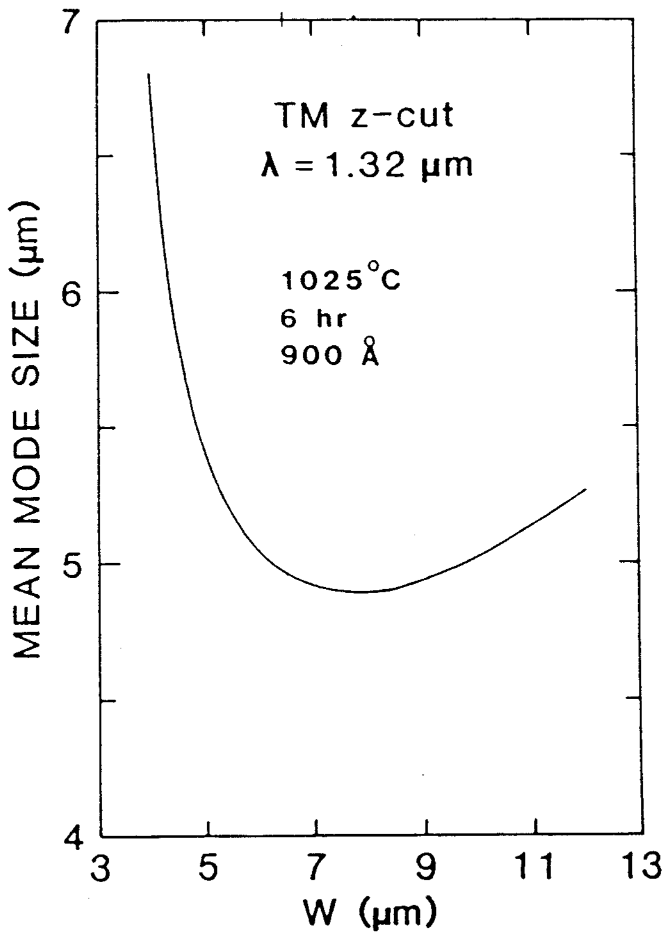

Figure 3 Calculated Ti:$LiNbO_3$ mean mode size at full width half intensity.

Control of the diffusion depth permits a method of controlling the mode size once the strip width is chosen. The mode width is relatively insensitive to changes of the diffusion depth. The vertical mode size, however, increases with increasing diffusion depth. The choice of metal thickness for fixed W and D is dictated by the desire to operate close to the cutoff of the second-order mode to ensure low propagation and bending losses of the fundamental mode. For single-mode propagation and low losses at 1.3 μm, the diffusion depth is from W/2 to W/4, that is, the ratio of the strip width to the diffusion depth W/D is from 2 to 4 depending on the application.

Using equations (1) and (2) in this report and the field expressions of Reference [6] with the following initial parameters: T = 1025 °C, t = 6 hours and W = 8 μm at 1.3 μm wavelength, the dependence of ΔN on τ is illustrated in Figure 4. This shows a clear threshold behaviour. As the thickness is increased from zero, the first effect is to begin to reduce the size of the mode, which is much larger than the waveguide size. Until the mode is drawn within the waveguide, the effective index difference is very small, because the overlap is poor. Once the mode size is roughly the waveguide size, there is little advantage to reduce the mode size further, as the overlap is good. At this point, changes in the metal thickness are directly reflected in increases in the effective index difference. It is because of this threshold behaviour that the tolerance on metal thickness is particularly stringent compared to other parameters. Although the required metal thickness is roughly 0.1 μm at 1.3 μm operating wavelength, the single-mode region of good confinement extends over a range of 0.02 μm. That is, the thickness of the deposited titanium layer before oxidation, τ, is roughly 2.5 to 3% of the diffusion depth D. In this region, the mode size hardly changes; rather, by comparison, the rate of the decaying tails of the mode profile change radically. These tails and therefore the metal thickness strongly influence the inter-waveguide coupling coefficient and the bending loss.

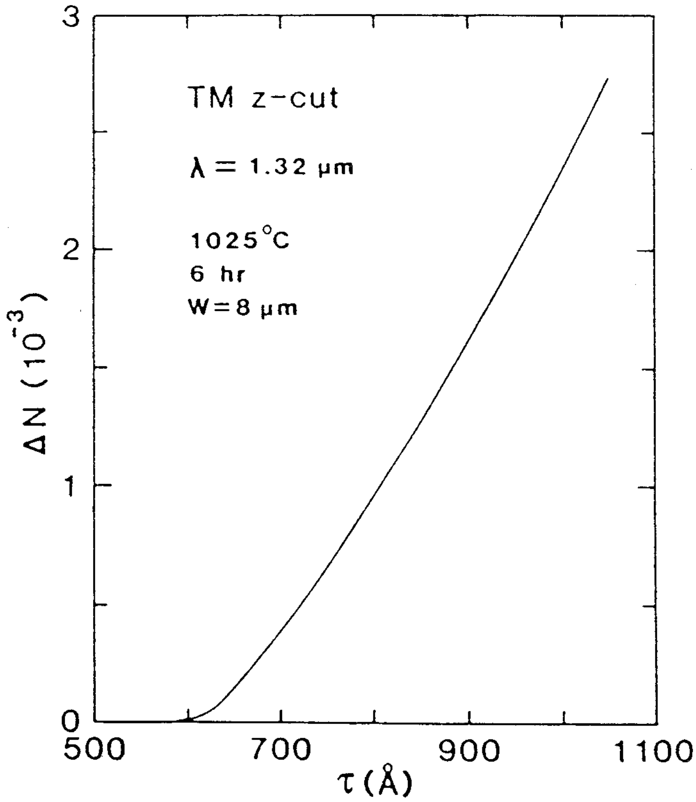

Figure 4 Calculated Ti:$LiNbO_3$ effective index difference.

3 CONCLUSIONS

For low-loss and single-mode propagation, the optimised dimensions and fabrication parameters are as follows:

metal strip width, W = 5 to 6 λ_o;
diffusion depth, D = W/4 to W/2; and
metal thickness, τ = 0.025*D to 0.03*D (by electron-beam deposition).

For the Y-branch interferometer at 1.3 μm operating wavelength, the following dimensions and fabrication parameters are chosen:

metal strip width, W = 7 μm;
diffusion depth, D = 3.5 μm; and
metal thickness, τ = 0.1 μm.

Assume that for congruent $LiNbO_3$ composition (ca. 48.6 mol % Li_2O), the value for D_o and T_A is given in Table 1 as 2.5×10^{-4} cm^2/s and 2.55×10^4 °K respectively. Taking the diffusion temperature T as 1025 °C, the diffusion time t is 11.6 hours which is calculated from equation (1d), that is,

$$t = D^2/\{4^*D_o^*[\exp(-T_A/(T+273))]\}.$$

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One of the goals of technology-based activities within the Electronic Warfare Division is to facilitate the development within Australia, of facilities and a capability to manufacture sophisticated, high-speed electro-optic devices, in particular, the integrated optical amplitude modulator and integrated optical switch, for use in microwave and millimetre-wave systems for the Australian Defence Force (ADF). An initial step towards this goal would be to produce a low-loss and single-mode propagation optical channel waveguide using titanium-indiffused lithium niobate (Ti:$LiNbO_3$). As no dimensions and fabrication parameters have yet been optimised, this technical report provides preliminary design data which optimises these parameters. Depending on its application, the optimised dimensions and fabrication parameters are as follows:

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